

PROPOSED FOUR ¼ TURN METRIC TO SIMULATE ROLLOVER CRASHES

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ABSTRACT

Rollovers are injurious crash events, causing a disproportionate amount of Harm. Current rollover metrics, Critical Sliding Velocity, Tilt Table Ratio, etc are based on turning a vehicle onto its side (one ¼ turn). ¼ turn rollovers account for 6.9% of Abbreviated Injury Scale (AIS) 3 to 6 injuries, whereas four ¼ turn rollovers (one full revolution) account for 69.5% of AIS 3 to 6 injuries. This paper proposes a four ¼ turn rollover metric based on vehicle geometry and mass.

INTRODUCTION

Rollovers as a single vehicle crash event are over represented by the amount of Harm (Harm is defined as the sum of all the injured people weighted in proportion to the outcome, as represented by the cost of the most severe injury). Herbst¹ et al presented data relating to US passenger cars “*rollover accidents pose a serious cost to society, while they account for 10% of all passenger car accidents they cause 20% of the Harm*”. The disproportionate level of Harm is due to the increased instance of head, neck and spinal injuries in rollover crashes.

In an Australian based study on rollover Reznitzer² et al, stated that; “*rollover crashes are common cause of occupant injury especially on non-urban roads. Their importance increases with injury severity: they constitute 19% of the occupant fatalities in Australia. This percentage rises to 44% in rural Western Australia and 54% in rural Northern Territory.*”

Snyder³ et al found that as a class of vehicles 4x4's are 3 to 5 times more prone to rollover than passenger vehicles. United States of America National Highway Traffic Safety Administration (NHTSA) data⁴ indicates that respective rollover rates of Pickups and Sports Utility Vehicles (SUV's) are 2.7 and 2.8 times that of passenger cars.

The need for analysis originates from the Australian Army's desire to protect all occupants carried in its

fleet of 4x4 Perentie vehicles (modified Landrover 110). Since introduction into service there have been in excess of 140 rollovers involving the Perentie 4x4 with 12 deaths, 64 serious injuries and 213 minor injuries and an estimated AU\$7.3M in vehicle repair, replacement and personnel injuries.

Current Roll Over Protective Structure standards were evaluated and reviewed and found lacking. Hence a test method was developed from various standards based on applying a defined amount of energy and force to the Protective Structure⁵. In the developed test method the amount of energy and force applied is derived from the vehicle geometry and mass.

¼ TURN METRIC

Current Rollover metrics, Critical Sliding Velocity (CSV) (figure 1), Tilt Table Ratio (figure 2), Side Pull Ratio and Stability Factor are based on turning a vehicle on to its side (one ¼ turn).

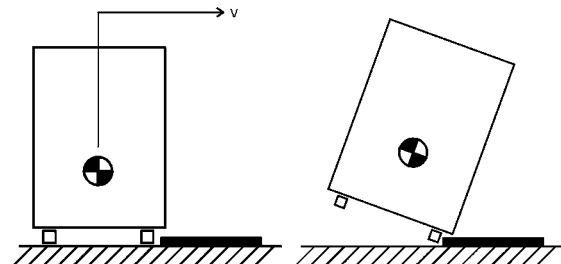


Figure 1. Illustration of CSV.

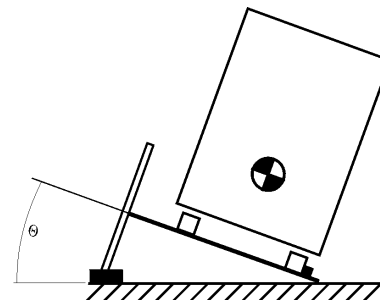


Figure 2. Illustration of Tilt table test

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There has been an ongoing debate in the area of rollover research about:

- Is whether the roof crushes the occupants or are the occupants impacting into the roof (diving injury).
- What is an acceptable level of roof crush, if any, is roof crush a measure of rollover severity.

The debate is useful in that a Roll Over Protection System should account for both issues. The occupant impacting into the roof is a function of the seat and restraint system and roof crush is a function of the structural performance of the vehicle.

One $\frac{1}{4}$ turn rollovers account for 6.9% of AIS 3 to 6 injuries, whereas four $\frac{1}{4}$ turn rollovers (one full revolution) account for 69.5% of AIS 3 to 6 injuries⁶. A possible reason is that with each subsequent impact the occupant is thrown further out of position rendering the restraint systems (Lap Sash seatbelts and Seats) ineffective with respect to rollover. A four $\frac{1}{4}$ turn rollover metric should enable the development of inputs (energy, force and direction) for both structural and restraint requirements.

Hight⁷ et al presented a paper on rollover and the injuries that result. The paper is comprehensive involving detailed examination of 139 vehicle rollovers with a typical spread of injuries 66% with less than or equal to AIS 2 injuries, 17% with AIS 2 to 5 and 17% fatalities. The two key findings relevant to this paper are:

- A rollover deceleration rate was between 0.40g and 0.65g.
- In a four $\frac{1}{4}$ turn rollover (one complete revolution of the vehicle) *“the heavy damage almost always occurs on the opposite side to the direction of roll”*.

Rollover unlike other crash modes is not well defined by a delta V profile. A contention of this paper is that a vehicle rollover protection system should be based on a four $\frac{1}{4}$ turn of the vehicle (as a minimum), and not a delta V.

The CSV is a tripping metric and is used to determine the minimum sideways sliding velocity of a vehicle to cause a one $\frac{1}{4}$ turn rollover when the tires or wheels impact a rigid or semi-rigid object. Typically the CSV metric is based on a rectangular shape, implying that the track width of a vehicle is equal to the roof width, which is often not the case. The profile of most vehicles can more accurately be described as trapezoidal in shape with the track and roof widths unequal in length but parallel to one another (figure 3).



Figure 3. Trapezoidal shape of typical 4x4.

The metric presented in this paper is based on the assumption that a rollover is separated into four distinct $\frac{1}{4}$ turn events. The metric utilises vehicle geometry, second moment of mass inertia and the centre of gravity location and extends the CSV metric for any $\frac{1}{4}$ turn rollover of a trapezoid shape. The CSV can then be used to define the Critical Sliding Energy for each $\frac{1}{4}$ turn.

The Critical Sliding Energy, lateral and rotational velocities can be used to assess injury outcomes and to define structural performance requirements for vehicle systems.

This paper is not concerned with cause of the rollover: launch, handling, slide and trip or landmine attack (in the case of Military vehicles) but the subsequent effect (figure 4).

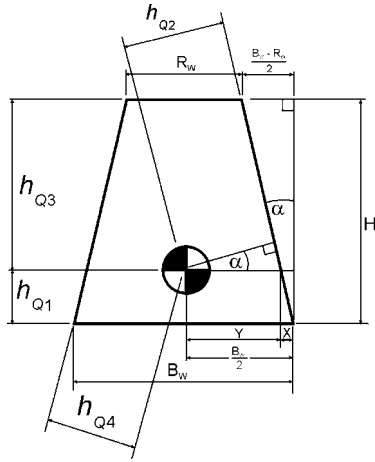


Figure 4. Perentie 4x4 rollover during handling trials.

Mathematics

The CSV can be calculated for a vehicle to roll one $\frac{1}{4}$ turn (ie. onto its side). This Velocity can be used to calculate sliding energy if the mass of the vehicle is known. By defining the profile of the vehicle in terms of the track, tyre width, roof width and centre of gravity height, the sliding energy can be calculated for any $\frac{1}{4}$ turn of the vehicle. The formulae for calculating trapezoidal calculation and the first, second, third and fourth $\frac{1}{4}$ turns are as follows:

Trapezoidal calculation



Using Simliar Triangles

$$\frac{B_w - R_w}{2H} = \frac{X}{h_{Q1}}$$

$$X = h_{Q1} \left(\frac{B_w - R_w}{2H} \right) \quad (1)$$

$$Y = \left(\frac{B_w}{2} \right) - X \quad (2)$$

Using Trigonometry

$$\cos \alpha = \frac{H}{\sqrt{\left(\frac{B_w - R_w}{2} \right)^2 + H^2}} \quad (3)$$

Substitute (1) into (2)

$$Y = \left(\frac{B_w}{2} \right) - h_{Q1} \left(\frac{B_w - R_w}{2H} \right) \quad (4)$$

Solve for h_{Q2}

$$h_{Q2} = Y \cos \alpha \quad (5)$$

Substitute (3) and (4) into (5)

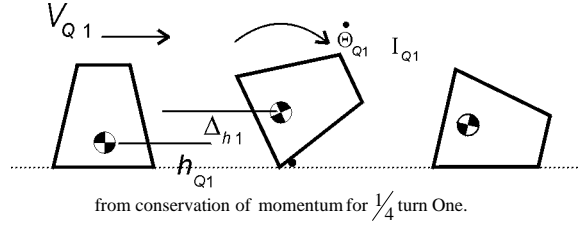
$$h_{Q2} = \left[\left(\frac{B_w}{2} \right) - h_{Q1} \left(\frac{B_w - R_w}{2H} \right) \right] \frac{H}{\sqrt{\left(\frac{B_w - R_w}{2} \right)^2 + H^2}} \quad (6)$$

Solve for h_{Q3}

$$h_{Q3} = H - h_{Q1} \quad (7)$$

$$h_{Q4} = h_{Q2} \quad (8)$$

1st $\frac{1}{4}$ turn sliding energy



$$I_{OQ1} \dot{\theta}_{Q1} = m v_{Q1} h_{Q1}$$

$$\dot{\theta}_{Q1} = \frac{m v_{Q1} h_{Q1}}{I_{OQ1}} \quad (9)$$

from energy

$$\frac{1}{2} I_{OQ1} \dot{\theta}_{Q1}^2 = m g \Delta h_1 \quad (10)$$

$$\Delta h_1 = \text{height rise} - h_{Q1}$$

$$\Delta h_1 = \sqrt{\left(\frac{B_w}{2} \right)^2 + h_{Q1}^2} - h_{Q1} \quad (11)$$

Substitute (9) and (11) into (10)

$$\frac{1}{2} I_{OQ1} \left(\frac{m v_{Q1} h_{Q1}}{I_{OQ1}} \right)^2 = m g \left(\sqrt{\left(\frac{B_w}{2} \right)^2 + h_{Q1}^2} - h_{Q1} \right)$$

$$\frac{v_{Q1}^2 m h_{Q1}^2}{2 I_{OQ1}} = m g \left(\sqrt{\left(\frac{B_w}{2} \right)^2 + h_{Q1}^2} - h_{Q1} \right)$$

$$v_{Q1} = \sqrt{\left(\frac{2 g I_{OQ1}}{m h_{Q1}^2} \right) \left(\sqrt{\left(\frac{B_w}{2} \right)^2 + h_{Q1}^2} - h_{Q1} \right)} \quad (12)$$

$$\text{but } I_{OQ1} = I_{CG} + m \left(\left(\frac{B_w}{2} \right)^2 + h_{Q1}^2 \right) \quad (13)$$

substitute (13) into (12)

$$v_{Q1} = \sqrt{\left(\frac{2 g}{m h_{Q1}^2} \right) \left(I_{CG} + m \left(\left(\frac{B_w}{2} \right)^2 + h_{Q1}^2 \right) \right) \left(\sqrt{\left(\frac{B_w}{2} \right)^2 + h_{Q1}^2} - h_{Q1} \right)} \quad (14)$$

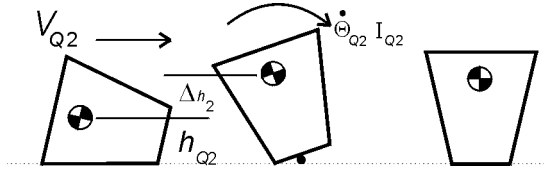
Sliding Energy

$$E_{Q1} = \frac{1}{2} m v_{Q1}^2 \quad (15)$$

Substitute (14) into (15)

$$E_{Q1} = \left(\frac{g}{h_{Q1}^2} \right) \left(I_{CG} + m \left(\left(\frac{B_w}{2} \right)^2 + h_{Q1}^2 \right) \right) \left(\sqrt{\left(\frac{B_w}{2} \right)^2 + h_{Q1}^2} - h_{Q1} \right) \quad (16)$$

2nd 1/4 turn sliding energy



from conservation of momentum for 1/4 turn Two

$$I_{OQ2} \dot{\theta}_{Q2} = m v_{Q2} h_{Q2}$$

$$\dot{\theta}_{Q2} = \frac{m v_{Q2} h_{Q2}}{I_{OQ2}} \quad (17)$$

from energy

$$\frac{1}{2} I_{OQ2} \dot{\theta}_{Q2}^2 = m g \Delta h_2 \quad (18)$$

$$\Delta h_2 = \text{height rise} - h_{Q2}$$

$$\Delta h_2 = \sqrt{\left(\frac{R_w}{2}\right)^2 + h_{Q3}^2} - h_{Q2} \quad (19)$$

Substitute (17) and (19) into (18)

$$\frac{1}{2} I_{OQ2} \left(\frac{m v_{Q2} h_{Q2}}{I_{OQ2}} \right)^2 = m g \left(\sqrt{\left(\frac{R_w}{2}\right)^2 + h_{Q3}^2} - h_{Q2} \right)$$

$$\frac{v_{Q2}^2 m h_{Q2}^2}{2 I_{OQ2}} = m g \left(\sqrt{\left(\frac{R_w}{2}\right)^2 + h_{Q3}^2} - h_{Q2} \right)$$

$$v_{Q2} = \sqrt{\left(\frac{2 g I_{OQ2}}{m h_{Q2}^2} \right) \left(\sqrt{\left(\frac{R_w}{2}\right)^2 + h_{Q3}^2} - h_{Q2} \right)} \quad (20)$$

$$\text{but } I_{OQ2} = I_{CG} + m \left(\left(\frac{R_w}{2}\right)^2 + h_{Q3}^2 \right) \quad (21)$$

substitute (21) into (20)

$$v_{Q2} = \sqrt{\left(\frac{2 g}{m h_{Q2}^2} \right) \left(I_{CG} + m \left(\left(\frac{R_w}{2}\right)^2 + h_{Q3}^2 \right) \right) \left(\sqrt{\left(\frac{R_w}{2}\right)^2 + h_{Q3}^2} - h_{Q2} \right)} \quad (22)$$

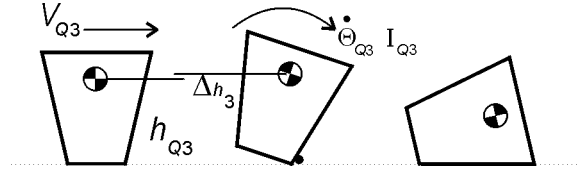
Sliding Energy

$$E_{Q2} = \frac{1}{2} m v_{Q2}^2 \quad (23)$$

Substitute (22) into (23)

$$E_{Q2} = \left(\frac{g}{h_{Q2}^2} \right) \left(I_{CG} + m \left(\left(\frac{R_w}{2}\right)^2 + h_{Q3}^2 \right) \right) \left(\sqrt{\left(\frac{R_w}{2}\right)^2 + h_{Q3}^2} - h_{Q2} \right) \quad (24)$$

3rd 1/4 turn sliding energy



from conservation of momentum for 1/4 turn Three

$$I_{OQ3} \dot{\theta}_{Q3} = m v_{Q3} h_{Q3}$$

$$\dot{\theta}_{Q3} = \frac{m v_{Q3} h_{Q3}}{I_{OQ3}} \quad (25)$$

from energy

$$\frac{1}{2} I_{OQ3} \dot{\theta}_{Q3}^2 = m g \Delta h_3 \quad (26)$$

$$\Delta h_3 = \text{height rise} - h_{Q3}$$

$$\Delta h_3 = \sqrt{\left(\frac{R_w}{2}\right)^2 + h_{Q3}^2} - h_{Q3} \quad (27)$$

Substitute (25) and (27) into (26)

$$\frac{1}{2} I_{OQ3} \left(\frac{m v_{Q3} h_{Q3}}{I_{OQ3}} \right)^2 = m g \left(\sqrt{\left(\frac{R_w}{2}\right)^2 + h_{Q3}^2} - h_{Q3} \right)$$

$$\frac{v_{Q3}^2 m h_{Q3}^2}{2 I_{OQ3}} = m g \left(\sqrt{\left(\frac{R_w}{2}\right)^2 + h_{Q3}^2} - h_{Q3} \right)$$

$$v_{Q3} = \sqrt{\left(\frac{2 g I_{OQ3}}{m h_{Q3}^2} \right) \left(\sqrt{\left(\frac{R_w}{2}\right)^2 + h_{Q3}^2} - h_{Q3} \right)} \quad (28)$$

$$\text{but } I_{OQ3} = I_{CG} + m \left(\left(\frac{R_w}{2}\right)^2 + h_{Q3}^2 \right) \quad (29)$$

substitute (29) into (28)

$$v_{Q3} = \sqrt{\left(\frac{2 g}{m h_{Q3}^2} \right) \left(I_{CG} + m \left(\left(\frac{R_w}{2}\right)^2 + h_{Q3}^2 \right) \right) \left(\sqrt{\left(\frac{R_w}{2}\right)^2 + h_{Q3}^2} - h_{Q3} \right)} \quad (30)$$

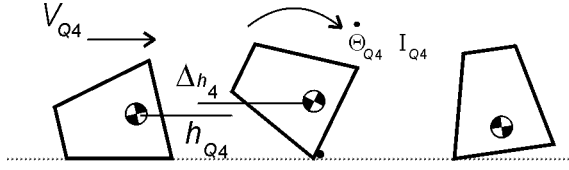
Sliding Energy

$$E_{Q3} = \frac{1}{2} m v_{Q3}^2 \quad (31)$$

substitute (30) into (31)

$$E_{Q3} = \left(\frac{g}{h_{Q3}^2} \right) \left(I_{CG} + m \left(\left(\frac{R_w}{2}\right)^2 + h_{Q3}^2 \right) \right) \left(\sqrt{\left(\frac{R_w}{2}\right)^2 + h_{Q3}^2} - h_{Q3} \right) \quad (32)$$

4th 1/4 turn sliding energy



from conservation of momentum 1/4 turn Four

$$I_{OQ4} \dot{\theta}_{Q4} = m v_{Q4} h_{Q4}$$

$$\dot{\theta}_{Q4} = \frac{m v_{Q4} h_{Q4}}{I_{OQ4}} \quad (33)$$

from energy

$$\frac{1}{2} I_{OQ4} \dot{\theta}_{Q4}^2 = m g \Delta h_4 \quad (34)$$

$$\Delta h_4 = \text{height rise} - h_{Q4}$$

$$\Delta h_4 = \sqrt{\left(\frac{B_w}{2}\right)^2 + h_{Q1}^2} - h_{Q4} \quad (35)$$

Substitute (33) and (35) into (34)

$$\frac{1}{2} I_{OQ4} \left(\frac{m v_{Q4} h_{Q4}}{I_{OQ4}} \right)^2 = m g \left(\sqrt{\left(\frac{B_w}{2}\right)^2 + h_{Q1}^2} - h_{Q4} \right)$$

$$\frac{v_{Q4}^2 m h_{Q4}^2}{2 I_{OQ4}} = m g \left(\sqrt{\left(\frac{B_w}{2}\right)^2 + h_{Q1}^2} - h_{Q4} \right)$$

$$v_{Q1} = \sqrt{\left(\frac{2 g I_{OQ4}}{m h_{Q4}^2} \right) \left(\sqrt{\left(\frac{B_w}{2}\right)^2 + h_{Q1}^2} - h_{Q4} \right)} \quad (35)$$

$$\text{but } I_{OQ4} = I_{CG} + m \left(\left(\frac{B_w}{2}\right)^2 + h_{Q1}^2 \right) \quad (36)$$

substitute (36) into (35)

$$v_{Q4} = \sqrt{\left(\frac{2 g}{m h_{Q4}^2} \right) \left(I_{CG} + m \left(\left(\frac{B_w}{2}\right)^2 + h_{Q4}^2 \right) \right) \left(\sqrt{\left(\frac{B_w}{2}\right)^2 + h_{Q1}^2} - h_{Q4} \right)} \quad (37)$$

Sliding Energy

$$E_{Q4} = \frac{1}{2} m v_{Q4}^2 \quad (38)$$

Substitute (37) into (38)

$$E_{Q4} = \left(\frac{g}{h_{Q4}^2} \right) \left(I_{CG} + m \left(\left(\frac{B_w}{2}\right)^2 + h_{Q4}^2 \right) \right) \left(\sqrt{\left(\frac{B_w}{2}\right)^2 + h_{Q1}^2} - h_{Q4} \right) \quad (39)$$

1/4 turn energy: This is the sum of subsequent 1/4 turns energies. In the case of four 1/4 turns it would be:

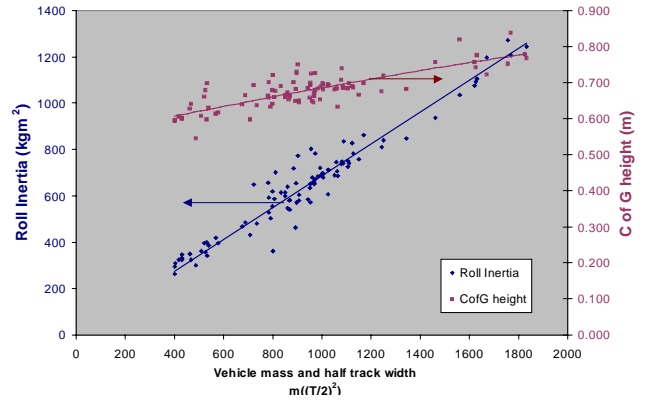
$$E_{\text{Rollover}} = E_{Q1} + E_{Q2} + E_{Q3} + E_{Q4} \quad (40)$$

In-order for the vehicle to complete a four 1/4 turn rollover E_{Rollover} must be available at the start of the rollover, however each $E_{Q1, 2, 3 \text{ or } 4}$ represents the Energy that the structure and the surface impacted must adsorb. Kecman⁸ et al in a review of the work done developing Rollover Protection Standards for Omnibuses states; “the author’s experience indicates that the energy can be reduced to the level specified in Australian Design Rule (ADR) 59/00.” ADR 59/00 allows 62% of the available rollover energy to be absorbed by the structure. Hence a structural requirement can be based on 62% of the energy required for subsequent 1/4 turns (ie $0.62 \times E_{Q1}$).

Based on available energy the sliding velocity can be calculated from the available energy. The difference between subsequent sliding velocities can also be determined. The angular velocity can also be calculated for each 1/4 turn.

Vehicle Data Vehicle Inertia and Centre of Gravity data is not readily available from the Manufactures, however NHSTA have developed a sizeable database of most of the required parameters with the exception of tyre and roof width. Vehicle data has been presented by Winkler⁹ et al in '92, Garrett¹⁰ in '93, Lund et al and in '95 Heitzman¹¹ et al in '97. Current data is available from the NHSTA website¹².

The NHSTA website data was sorted by vehicle category. The following graph presents the data for Multi-Purpose Vehicles (MPV) and plots Roll Inertia and Centre of Gravity Height against vehicle mass times the square of half the track width.



Graph 1. MPV Roll Inertia and C of G height trends.

The curve trends and R^2 values are:

- Roll Inertia: $y = 0.6877x$ ($R^2 0.9405$)
- C of G: $y = -1 \times 10^{-8}x^2 + 0.0002x + 0.5476$ ($R^2 0.6875$)

In the absence of specific vehicle data the derived trends were used.

Accident Data

Two crashes are presented; the scenes were examined and documented by the Victorian Police Major Collision Investigation Unit. The vehicle speeds were calculated from the Yaw¹³ marks.

The first rollover crash involved a Mitsubishi Pajero, where the front seat passenger was unrestrained and thrown from the vehicle. The crash scene is shown in figure 5 and the Pajero is shown in figure 6. Structurally the Pajero has withstood the crash event quite well.



Figure 5. Pajero rollover crash scene.



Figure 6. Damage to Pajero.

The Pajero is estimated to have been travelling at 132km/h (1297kJ) and left the road in an attempt to correct the path. The Pajero driver oversteered and started to yaw. At a yaw angle of approximately 42°

the Pajero tripped and rolled 73m. It is estimated that the Pajero completed 3 complete rotations or twelve ¼ turns, completing the crash on its wheels, as shown in figure 6.

Using the method detailed in this paper the energy to complete each ¼ turn was calculated as:

- $E_{Q1} = 23.8\text{kJ}$
- $E_{Q2} = 50.2\text{kJ}$
- $E_{Q3} = 3.6\text{kJ}$ and
- $E_{Q8} = 19.7\text{kJ}$

This equates to 97.3kJ for a complete rotation and 292kJ for 3 complete rotations or twelve ¼ turns.

It is estimated that the Pajero absorbed:

- 305kJ in completing the yaw prior to tripping.
- 298kJ sliding across the asphalt road.
- 232 sliding across the verge.
- 171kJ (15% of the above estimated energy) attributed to heat, noise, and deformation of the structure^{14, 15}.

The second rollover crash involved a Toyota Landcruiser (Series 55). The crash scene is shown in figure 7 and the Landcruiser is shown in figure 8. Structurally the Landcruiser has not withstood the crash and the occupant space is significantly encroached.



Figure 7. Landcruiser crash scene.



Figure 8. Damage to Landcruiser.

The Landcruiser is estimated to have been travelling at 129km/h (1243kJ) and left the road. In an attempt to correct the path of the Landcruiser the driver oversteered and started to yaw. At a yaw angle of approximately 51° the Landcruiser tripped and rolled 53m. It is estimated that the Landcruiser completed four ¼ turns (1 complete rotation sideways) and then bounced twice, completing 2½ rotations end for end, completing the crash on its roof, as shown in figure 8.

Using the method detailed in this paper the energy to complete each ¼ turn was calculated as:

- $E_{Q1} = 26.2\text{kJ}$
- $E_{Q2} = 42.8\text{kJ}$
- $E_{Q3} = 6.7\text{kJ}$ and
- $E_{E4} = 17.4\text{kJ}$

This equates to 93.1kJ for a complete rotation.

It is estimated that the Landcruiser absorbed:

- 601kJ in completing the yaw prior to tripping.
- 139kJ siding across the road and verge.
- 175kJ in first bounce.
- 103kJ in the second bounce.
- 132kJ (11% of the above estimated energy) attributed to heat, noise, and deformation of the structure.

It is worthwhile to note that in the case of both the Pajero and the Landcruiser, that Q_2 represents the largest energy 50.2kJ and 42.8kJ respectively. This equates to the empirical finding of Hight⁷ et al that the second impact was the worst.

CONCLUSION

Current metrics based on CSV and Tilt Table Ratio are based on only one ¼ turn. Four ¼ turns are more injurious and account for 69.5% of AIS 3 to 6 injuries.

This paper has presented an energy method metric, which is based on a trapezoidal vehicle shape, expansion of the CSV calculation and vehicle mass properties. Outputs of the metric are energy, lateral velocity and rotational velocity for each subsequent ¼ turn.

The output can be used to define the structural and restraint performance criteria for a specific vehicle rollover crash.

Two rollover crashes were presented and the energy balanced.

Further research will be carried out examining:

- Additional rollover cases.

- Inertia and Centre of Gravity data.
- Structural capacities of vehicles.
- Different Vehicle shapes.

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